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Rising Energy and Feedstock Prices Affect the Cost of Green and Blue Hydrogen

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Steam methane reforming units (SMR) have been technically mastered nowadays, but most installed units are large-capacity units. In addition, the hydrogen that is produced does not reach the required purity. It would have to be purified, which increases the investment and operating costs. The development of a small SMR is described here, and marketed equipment is listed. The production of blue hydrogen by steam reforming or of green hydrogen by hydrolysis of water is an option as a source of hydrogen for these units. Hydrogen production by water electrolysis is technically more straightforward, but it requires a significant electricity supply at high current loads. This paper provides an overview of the principal published data of equipment manufacturers and essential scientific articles on both technical and economic issues of hydrogen production for these purposes. The paper contributes an assessment of recommended methods for the conversion of CAPEX units of different capacities and a rough estimate of the growth of feedstock and energy prices to OPEX. The production price of hydrogen from SMRs has increased by approximately 2.18 times and the production price of hydrogen from electrolysis units has increased by approximately 1.53 times due to the increase in the price of raw materials and electricity.

1. Introduction

Reducing the carbon footprint caused by transport is already in the implementation stage. For public transport, where the means of transport are concentrated in a single owner, the development and the implementation of vehicles (buses and trucks) and trains powered by environment-friendly hydrogen combustion are under consideration. At the beginning of the 21st century, the network of hydrogen refuelling stations was sparse, with only dozens of stations around the world. Nowadays, however, there are hundreds or even thousands of stations. The concepts differ mainly in terms of centralization or decentralization of the units, and how hydrogen is transported and stored. Our search contains many papers and company materials. Several papers cited in the text have been published on mechanical, technological, economic, and prognostic aspects, providing sufficient but disparate and scattered information on the state of the art. The knowledge gap is in the development of methods to purify hydrogen produced on SMR units and in the development of technologies to produce electrolytic hydrogen and reduce its production cost by obtaining electricity from renewable sources, mainly photovoltaic and wind energy. The recent drastic change in the price of feedstock and electricity prices, which has not yet been assessed in the available sources, is a significant change in the assessment of the viability of the hydrogen route. The paper presents the principal works, verified technical and economic data, and parameters. It also estimates how the drastic increase in natural gas and energy prices will affect the cost of hydrogen produced by the two basic methods, i.e., steam-methane reforming (SMR) and water electrolysis, and therefore their priority. Hydrogen parameters for fuel cells must meet ISO requirements. Achieving these parameters must be considered when designing production technologies and equipment and when contracting and approving lines. Hydrogen fuel quality and product specifications are specified by ISO14687:2019(en). In most cases, water electrolysis meets the requirements of so-called green hydrogen. So-called blue hydrogen produced by SRM contains impurities and contaminants that must be removed. Pressure Swing Adsorption (PSA) units are therefore required in hydrogen production lines for fuel cells.

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2. Small steam-methane reforming units

Detailed designs for large and small-scale Steam Methane Reforming (SMR) units have been developed specifically for hydrogen production. The small-scale design assumes a methane feed rate of 27 $Sm^3\ h^{-1}$ and production of 4.5 kg h^{-1} of hydrogen, while the large-scale design uses a methane feed rate of 187,000 $Sm^3\ h^{-1}$ and production of ~ 45,000 kg h^{-1} of hydrogen. For small-capacity units, the technological scheme and the machine layout are partially simplified compared to large-capacity units, e.g. secondary reforming is omitted, there is a lower level of heat recovery integration, and gas purification is performed only by PSA, without an amine scrubber. Figure 1 is a schematic representation of a typical small-scale unit presented in the report submitted by Nexant (2016).

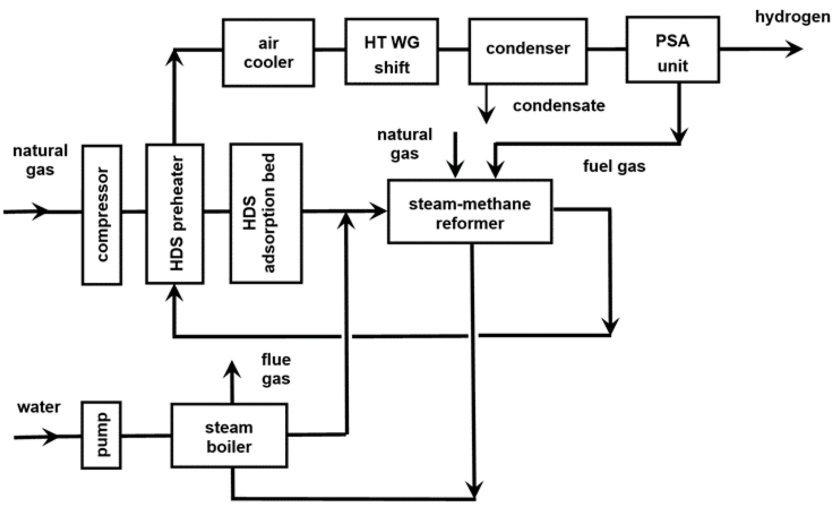

Figure 1: Technological scheme of a small capacity SMR unit (Nexant, 2006)

For hydrogen consumption in the range of 30 to 5,000 $Nm^3\ h^{-1}$ (i.e. from 2.7 to 450 kg h^{-1} of hydrogen), it is recommended to supply hydrogen through on-site production (Air Products, 2013). For these reasons, the development of small-scale hydrogen production units has been quite dynamic over the past 20 years. As part of the transition to a hydrogen economy, the International Energy Agency (IEA) established a group focused on small-scale reformers for on-site hydrogen production. According to Schjølberg et al. (2012), the group recommended the following capacities for on-site hydrogen generators: 100 $Nm^3\ h^{-1}$, 300 $Nm^3\ h^{-1}$, and 500 $Nm^3\ h^{-1}$, i.e. 9, 27, and 45 kg h^{-1}, respectively 216, 648, and 1,079 kg d^{-1}. An overview of selected small-scale reforming unit types that have been marketed and their suppliers are given in Table 1.

Table 1: An overview of selected small-scale reforming units and their suppliers

Supplier	Capacity (kg $H_2\ h^{-1}$)	Hydrogen purity (%)	Note-capacities of the certain types
AIRGAS	By request	99.999	Floxal; capacity by purchaser requirement
AIR LIQUIDE	900 - 3,600	99.999 [*1]	SMR-X ; 10,000 - 40,000 $Nm^3\ h^{-1}$
AIR PRODUCTS	8.3 - 75	99.999	PRISM generator; 93 - 837 $Nm^3\ h^{-1}$
BayoTech Inc.	8.3 ; 20.8 ; 41.6	> 99.999	93; 232; 464 $Nm^3\ h^{-1}$
Linde Engineering	27 - 2,519	99.999	Hydroprime; 300 - 28,000 $Nm^3\ h^{-1}$

Note [*1] not specified in the datasheet, estimation according to the use of PSA unit.

2.1 A brief description of the process

The process involves the catalytic reaction between methane and steam to produce the synthesis gas. The synthesis gas is further processed through another catalytic step to increase the hydrogen fraction and decrease the CO via the water gas shift reaction. Finally, a purification step removes all other components to produce the hydrogen product. For small-capacity units, the technological scheme and the equipment layout are partially simplified, for example, by a lower degree of heat utilization and by gas purification only with PSA, without amine scrubbing. The scheme of the small capacity unit presented by Nexant (2016) is shown in Figure 1. The equilibrium conversion of methane under the given conditions is about 73 %. The hydrogen stream is purified with a 4-bed PSA. The 99.99 % pure hydrogen that is obtained contains less than 10 ppm CO. The exhaust from the PSA unit containing part of the hydrogen, residual CO, CO_2, nitrogen, and other components is used as fuel gas and is co-combusted with natural gas to heat the reactor (Nexant, 2006). The design of the heat exchangers is a standard design, without unique solutions to minimize costs. For example, air coolers are used, as they are considered more practical on a small scale. There is also an effort to use modular solutions (Sharma et al., 2019) and standardized capacities (Schjølberg et al., 2012).

2.2 SMR technical data

From the point of view of carbon capture and storage (CCS), the optimum reforming temperature is an important issue. The effect of reaction temperature on selected parameters and other important process parameters are recalculated according to Sharma et al. (2019) and are presented in Table 2. This table shows the specific consumption of natural gas (NG) and steam, thermal efficiency, and specific CO_2 emissions. Decreasing the reaction temperature increases the specific methane consumption per hydrogen produced due to reduced conversion. It increases the specific steam consumption, but the total specific natural gas consumption, including heating, decreases due to the lower reaction temperature, resulting in lower specific CO_2 emissions per hydrogen produced. The economic assessment of CCS on natural gas reforming was analysed by Cormos et al. (2018) for large capacity units.

Table 2: Steam methane reforming - small capacity unit - effect of reaction temperature, specific consumption of natural gas (NG) and steam, thermal efficiency, and specific CO_2 emissions; (recalculated data of Sharma et al., 2019)

Parameter	Reforming temperature		
	750 °C	800 °C	850 °C
Natural gas (NG) consumption for reforming reaction ($kg_{NG}\ kg_{H2}^{-1}$)	3.064	2.72	2.552
Steam consumption for reforming reaction ($kg_{H2O}\ kg_{H2}^{-1}$)	12.348	10.962	10.287
Fuel consumption ($kg_{NG}\ kg_{H2}^{-1}$)	0.096	0.464	0.664
Total NG consumption ($kg_{NG}\ kg_{H2}^{-1}$)	3.16	3.184	3.216
CO_2 in syngas after water gas shift (WGS) ($kg_{CO2}\ kg_{H2}^{-1}$)	6.028	5.808	5.676
Thermal efficiency (-)	0.74	0.735	0.728
Total CO_2 emissions ^{*1} ($kg_{CO2}\ kg_{H2}^{-1}$)	8.91	8.976	9.064
Total CO_2 emissions ^{*1} ($g_{CO2}\ kWh_{LHV}^{-1}$)	662	667	673

Note ^{*1} excluded capture of the CO_2 contained in syngas after WGS.

2.3 Economics of small-capacity SMR units

The specific price of H_2 produced at the SMR mainly depends on the production capacity of the line. The specific price increases through the line for low-capacity lines, as shown in the graph in Figure 2a. 8,000 working hours per year were considered. The graph is constructed by recalculating the data of Ferreira-Aparicio et al. (2008). The shape of the graph is demonstrated, but the absolute figures for the production cost of hydrogen vary considerably. Besides the line capacity, the hydrogen price is also affected by the temperature of the reactor, the type of line and process treatments, and the location that is considered. Thomas et al. (2009) compared central and distributed hydrogen production costs. They state the summary of input data and the resulting hydrogen cost estimates in \$ kg^{-1} for hydrogen fuelling systems with 578 kg d^{-1} and 1,500 kg d^{-1} capacity in manufacture quantities of 1,100 and 500 each. Schjølberg et al. (2012) and Thomas et al. (2009) also dealt with cost estimates of reforming units.

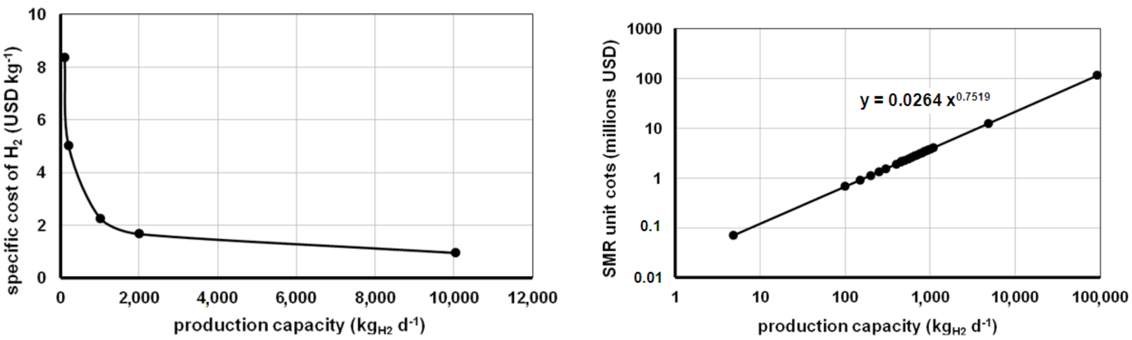

Figure 2: Steam methane reforming: a) dependence of the specific cost of H_2 on the production capacity of the line (left), b) CAPEX dependency on production capacity for an uninstalled SMR unit without CCS (right)

2.4 Impact of equipment size on CAPEX

The conversion of equipment and line prices to different operating capacities can be calculated according to the following equation

$$C_1=C_2 (Q_1/Q_2)^{\alpha}, \quad (1)$$

where C_1 is the price corresponding to operating capacity Q_1, C_2 is the price corresponding to capacity Q_2, and α is a semi-empirical constant. The theoretical value of α is 0.67. NREL papers report a value of 0.77 for four small-scale methane technologies. Gao and Zhang (2022) report a value of 0.95, which seems to have limited validity in their work. Reviewing the available literature, company data, and confidential quotations valid for uninstalled SMRs without CCS, a value of 0.7505 was obtained for production units involving hydrogen purification, including the PSA unit (see Figure 2b). The plausibility of the relationships is demonstrated by the agreement of the prices with the data obtained from quotations posted in 2022.

2.5 Impact of changes in energy costs and natural gas on OPEX

The OPEX layout for SMR was evaluated from the data presented by Ferreira-Aparacio et al. (2008) for natural gas conversion technologies, by Ayodele et al. (2020) for small-capacity units, and by Ferreira-Aparicio et al. (2008) for green hydrogen. Price changes constituting OPEX that unexpectedly occurred in 2022 are estimated in the middle column by commodity markets and Chemical Engineering Plant Cost Index. As a result of the calculation, we find the difference in operating costs between 2021 and 2022. It can be seen that the price changes had a more significant impact on the OPEX produced in the SMR unit. The change in the cost of electricity and NG in 2022 increased drastically. The OPEX of SMR increased 2.18 times and the OPEX of electrolytic hydrogen increased 1.53 times.

Table 3: Effect of costs of electricity and natural gas on the OPEX of the SMR and the electrolyser

Item	Steam-methane reformer (402 kg_{H2} d^{-1})				Electrolyser (500 kg_{H2} d^{-1})			
	Cost portion (%)	cost year 2021	(USD kg_{H2}^{-1}) year 2022	Cost change 22/21 (-)	Cost portion (%)	cost year 2021	(USD kg_{H2}^{-1}) year 2022	Cost change 22/21 (-)
Labor	8.5	0.196	0.211	1.08				
Annuity	28.0	0.643	0.656	1.02				
Capital costs	11.9	0.273	0.300	1.1	35.3	2.067	2.277	1.1
Natural gas	25.4	0.585	2.924	5				
Steam	13.6	0.312	0.437	1.4				
Electricity	10.2	0.234	0.421	1.8	60.5	3.549	6.388	1.8
Water	1.5	0.035	0.041	1.2	4.3	0.251	0.301	1.2
Others	1.0	0.023	0.025	1.1				
Total	100	**2.300**	**5.015**	**2.18**	100	**5.867**	**8.966**	**1.53**

3. Electrolysers for fuel cells

Water electrolysis can be classified according to the process temperature as i) low-temperature electrolysis and ii) high-temperature electrolysis, or according to electrolyte type as ii) alkaline electrolysis (AEL), ii) proton-selective membrane electrolysis (PEM), and iii) solid oxide electrolysis (SOEC).

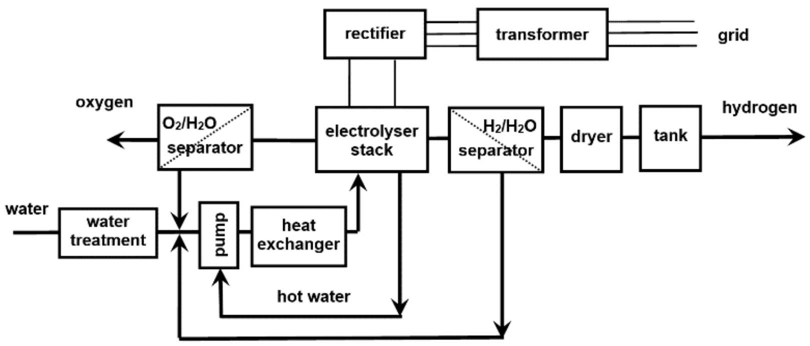

Figure 3: Technological scheme of the PEM electrolyser (Mayyas et al., 2019)

3.1 A brief description of the process

PEM electrolysers are more suitable for hydrogen purity and unit flexibility when hydrogen is produced for fuel cells. The scheme of the PEM electrolyser is shown in Figure 3. Drinking water is demineralised and deionised before electrolysis. The liquid water drops escaping in the formed gases are separated and are returned to the electrolyser. Finally, the hydrogen stream is dried to remove the rest of the moisture. For car fuelling, a dispenser with a high-pressure compressor is installed.

3.2 Technical data

An overview of selected small-scale electrolysers that have been marketed, and their suppliers, is given in Table 4.

Table 4: An overview of selected small-scale PEM electrolysers and their suppliers

Supplier	Capacity (kg H_2 h^{-1})	Hydrogen purity (%)	Specific energy consumption per stack (kWh kg_{H2}^{-1})	Specific energy consumption per unit (kWh kg_{H2}^{-1})	Note
NEL ASA	180 - 450	99.9995 *1	50		M series; 2,000 - 5,000 Nm^3 h^{-1}
NEL ASA	22; 44	99.9995 *1	50		M series containerized; 246; 492 Nm^3 h^{-1}
ITM Power	11; 36			64.3; 57.5	containerized; HGAS1SP; HGAS3SP; 122; 400 Nm^3 h^{-1}
Cummins Inc.	18; 22.5; 35.9; 45	99.998	40 - 48	54 - 55	200; 250; 400; 500 Nm^3 h^{-1}
AIR LIQUIDE	25 - 175	99.9998			HYOS-E; 278 – 1,949 Nm^3 h^{-1}

Note *1 purity when an optional high purity dryer is used.

3.3 Economics of green hydrogen

The cost of electricity is a significant cost item in hydrogen production. Further detailed data on CAPEX and OPEX costs for alkaline and PEM electrolysers is provided by Mayyas and Mann (2018). The precise cost breakdown for a PEM electrolyser, from complete to the stack, is presented by IRENA (2020).

4. Results and discussion

Hydrogen price figures vary considerably depending on the technology, production volume, country or region, and the stage of production and distribution at which the price is calculated. Forecasting giant Bloomberg pronounced that today blue hydrogen is cheaper to produce than its green equivalent. The underlying technology that strips hydrogen molecules from coal or gas is commercially mature, although the carbon capture component is not. In locations where natural gas is as cheap as $ 3 - 4 per million British thermal units (MMBtu), e.g., the U.S. and Canada, blue hydrogen can theoretically be produced for under $2 per kilogram. By contrast, green hydrogen costs over $ 4 per kilogram to make in the same locations (Bhavnagri, 2021). SGH2 Energy Global, LLC (2022) reported the following current prices: blue hydrogen - produced from natural gas paired with carbon capture and storage - costs between $ 5 and $ 7 per kg in the U.S., and between $ 7 and 11 in Europe and Australia. Green hydrogen produced through electrolysis using renewable power costs $ 10 - 15 per kg, depending on availability. However, it is indisputable that the current average selling retail price of hydrogen at filling stations in Germany is around EUR 16 kg_{H2}^{-1} (https://h2.live) and the average selling retail price was $ 16.51 kg_{H2}^{-1} in California in 2019 (Baronas et al., 2019). These prices must include production and other costs that make up the selling price, including profit. Recently, Gao and Zhang (2022) outlined their expectations about the future of H_2 production. A prognosis about future costs of H_2 focused on East Asia is discussed in ERIA (2019). Substantial cost savings by using solar energy are discussed by Vartiainen et al. (2022).

5. Conclusions

The paper has provided a list of publications and data essential for assessing and monitoring hydrogen production issues based on a critical search. A search for manufactured and distributed small-scale hydrogen production equipment has been conducted. The price conversion method has been reviewed, and the calculation equation has been refined for uninstalled SMR units without carbon capture. The equation can calculate the present CAPEX of such an SMR: CAPEX= $0.0264\times(\text{production in } kg_{H2}\ d^{-1})^{0.7519}$. The verification was carried out according to prices obtained from company quotations. Based on the operating cost structure, an estimate has been made of the impact of changes in the price of natural gas and energy (electricity and steam) on increases in the price of hydrogen produced in low-capacity SMR units and hydrogen made electrolytically. The results show that an effective way to reduce the price of hydrogen is through renewable energy, mainly through solar and wind power or a combination of both. The production price of hydrogen from SMRs has increased by approximately 2.18 times and the price of hydrogen from electrolysis units has increased by about 1.53 times, due to rises in raw materials and electricity prices. The perspectives of a hydrogen route in our opinion, are bright. A reduction in the price of hydrogen produced by SMR is possible only by improving CCS and through a carbon penalty policy. Future progress in electrolytic technology and the utilization of solar and wind energy can reduce the hydrogen cost to about 40 %. When considering production and sales prices, we must not forget the emission charges, which are particularly high for SMRs. This paper is intended primarily for designers, investors, and implementers of small-scale hydrogen sources to supplement the necessary design and economic data.

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